Relic Neutrinos

- **Relic Neutrinos in the Standard Model**
- **Direct Detection?**
- **Nucleosynthesis**
- **Beyond the Standard Model**

Expectations for the Relic Neutrinos

- $\nu_i, \bar{\nu}_i$ decoupled at $T_D \sim$ few MeV

$$
\begin{aligned}
f_{\nu_i} &= F_{eq}(p', m_i, \mu_{D_i}, T_D) \\
&= \left[\exp\left(\frac{(p'^2 + m_i^2)^{1/2} - \mu_{D_i}}{T_D}\right) + 1\right]^{-1} \\
f_{\bar{\nu}_i} &= F_{eq}(p', m_i, -\mu_{D_i}, T_D)
\end{aligned}
$$

- Subsequently, p' redshifted to $p = p'/\eta$, where $\eta \equiv R(t)/R(t_D)$

$$
\begin{aligned}
f_{\nu_i} &\rightarrow F_{eq}(p', m_i, \mu_{D_i}, T_D) \\
&= F_{eq}(p, m_i/\eta, \mu_{D_i}/\eta, T_D/\eta) \\
&= \left[\exp\left(\frac{(p^2 + m_{eff_i}^2)^{1/2} - \mu_i}{T_\nu}\right) + 1\right]^{-1}
\end{aligned}
$$

$$
m_{eff_i} \equiv \frac{m_i}{\eta} \ll m_i, \quad T_\nu \equiv \frac{T_D}{\eta} = \left(\frac{4}{11}\right)^{1/3} T_\gamma \sim 1.9K, \quad \mu_i \equiv \frac{\mu_{D_i}}{\eta}
$$

$(\mu_i \rightarrow -\mu_i \text{ for } \bar{\nu}_i)$

- *Form* of relativistic thermal distribution, but (negligible) $m_{eff} \ll T_\nu$
- Actually decoupled and may be non-relativistic

- **For $\mu_i = 0$,**

$$
\begin{aligned}
N_{\nu_i} &= N_{\bar{\nu}_i} = \int \frac{d^3p}{e^{p/T_\nu} + 1} \sim 50/cm^3 \\
\langle p \rangle &\sim 3.2T_\nu \sim 5.2{\times}10^{-4}\ eV
\end{aligned}
$$

- **For hierarchical pattern**

$$m_3 \sim 0.05\ eV, \quad m_2 \sim 0.005\ eV, \quad m_1 \ll m_2$$

$$(\langle v_3 \rangle \sim 10^{-2}, \quad \langle v_2 \rangle \sim 10^{-1})$$

- **For degenerate pattern,** $m_1 \sim m_2 \sim m_3 \lesssim 0.23\ eV$ **(WMAP),**

$$\langle v_i \rangle \sim 2 \times 10^{-3} \left(\frac{0.23\ eV}{m_i} \right)$$

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- **Clustering?**

$$v_{\rm esc} \sim 10^{-4}\ (\text{Sun}),\ 2 \times 10^{-3}\ (\text{Galaxy}),\ 3 \times 10^{-3}\ (\text{Large Cluster})$$

  - **Little effect on velocities except degenerate case**
  - **Little clustering unless** $m_i \gtrsim 0.3\ eV$**, and then on supercluster scale (Singh, Ma)**

- **Non-zero asymmetry, $\mu_i \neq 0$:**

$$N_{\nu_i} - N_{\bar{\nu}_i} = \frac{T_\nu^3}{6}\left[\xi_i + \frac{\xi_i^3}{\pi^2}\right], \quad \xi_i \equiv \frac{\mu_i}{T_\nu}$$

BBN + CMB: $-0.01 < \xi_e < 0.22, \quad |\xi_{\mu,\tau}| < 2.6$

CMB + BBN + equilibration: $|\xi_i| < 0.07$ (Lunardini, Smirnov; Dolgov et al; Wong; Abazajian, Beacom, Bell) **(unless new energy source)**

But, naive expectation is $|\xi| = O(10^{-11})$

Implications

- **Direct Detection**
- **CMB, large scale structure**
  - $\sum_i m_i < 0.71\ eV$ **(small scale suppression)**
  - $|\xi_i| < O(2)$ **(onset of matter domination)**
- **BBN**
  - **Sterile Neutrinos**
  - **Dirac neutrinos**
    - **In Standard Model**
    - **With new interactions** (Barger, PL, Lee)
  - **Hiding new degrees of freedom** (Barger, Kneller, PL, Marfatia, Steigman)

Direct Detection

- Incoherent scattering from fixed target

$$\sigma_\nu \sim G_F^2 E_\nu^2 \sim 10^{-62}\, cm^2\, (m_\nu = 0),\;\; 10^{-58}\, cm^2\, (m_\nu \sim 0.1\, eV)$$

  - Rate per target atom: $\sigma_\nu j_\nu \sim 10^{-42}\;\; (10^{-38})/yr$ for $j_\nu \sim 3{\times}10^{12}/cm^2 - s$
  - For $N \sim 10^{21}$ particles in coherence volume of radius $\lambda = 1/p \sim 2.4\, mm \rightarrow \sigma_\nu j_\nu N^2 \sim 1/yr$. Signal?
  - No practical G_F^2 detection schemes

- **Scattering of high energy cosmic ray neutrinos (Z-burst)** (Weiler)

$$\nu_i \bar{\nu}_i \longrightarrow Z \longrightarrow \text{particles},$$

at $E^R \sim 4\times 10^{21}\ eV/m_\nu(eV)$. Secondary nucleons after distance D:

$$E_p \sim \frac{10^{21}\times(0.8)^{D/6Mpc}}{(m_\nu/0.1\ eV)}$$

  - Account for $E_p >$ GZK? (Best fit $m_\nu = 0.26^{+0.20}_{-0.14}\ eV$, Fodor, Katz, Ringwald)
  - Future observation? Depends on unknown flux of UHEν

Forces, Torques on Macroscopic Objects

- Coherent forward elastic scattering. $\lambda \sim 2.4\ mm \gg$ atomic spacing suggests ray optics, with refractive indices

$$n_{\nu,\bar{\nu}} - 1 = \frac{2\pi}{p^2} \sum_a N_a f^a_{\nu,\bar{\nu}}(0)$$

$$f^a_{\nu,\bar{\nu}}(0) = \mp \frac{1}{\pi} \frac{G_F E}{\sqrt{2}} K(p, m_\nu) \left[g^a_V + g^a_A \vec{\sigma}_a \cdot \hat{p} \right],$$

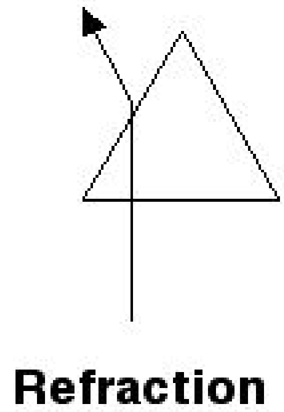
where $K \to (1, \frac{1}{2})$ for $(m_\nu = 0,\ p \ll m_\nu)$, and

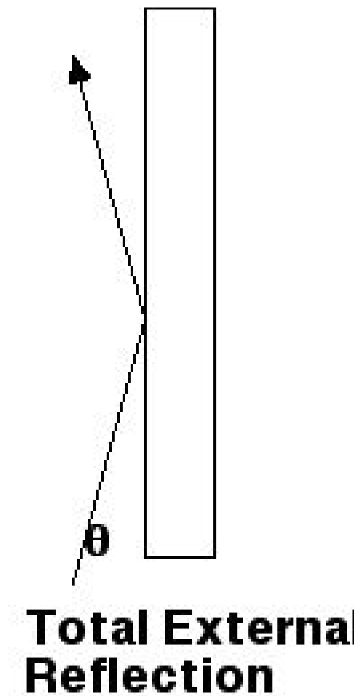
$$-L = \frac{G_F}{\sqrt{2}} \bar{\nu} \gamma_\mu (1 + \gamma_5) \nu \bar{\psi}_a \gamma^\mu (g^a_V + g^a_A \gamma_5) \psi_a$$

For polarized iron and SM couplings,

$$\begin{aligned} n_{\nu_e,\bar{\nu}_e} - 1 &= \mp 2.3 \times 10^{-10} [1 + 0.85 \langle \vec{\sigma}_e \rangle \cdot \hat{p}] \\ n_{\nu_\mu,\bar{\nu}_\mu} - 1 &= \pm 3.1 \times 10^{-10} [1 + 1.2 \langle \vec{\sigma}_e \rangle \cdot \hat{p}] \end{aligned}$$

- Net force from refraction for asymmetric geometry?
- Movement through ν sea needed?
- $\nu - \bar{\nu}$ cancellation?





- Total external reflection (Opher)
  - Net force of $O(G_F)$ for $\theta < \theta_c = \sqrt{2(1-n)} \sim 10\ \mu rad$ for $n < 1\ \ (\nu_e, \bar{\nu}_\mu, \bar{\nu}_\tau)$
  - No $\nu - \bar{\nu}$ cancellation
  - Need stack of reflectors and motion through ν rest frame
  - Concrete proposal (actually $O(G_F^{3/2})$) (Lewis)

- Effect actually vanishes to $O(G_F, G_F^{3/2})$ (PL, Leveille, Sheiman; Cabibbo, Maiani)
  - Total external reflection only occurs for reflector thickness $>$ skin depth $d \sim \lambda/\sqrt{1-n} = O(20\ m)$
  - Diffraction at ends unless length $L > 10^7\ m$

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- $O(G_F^2)$ allowed but too small

- Net torque allowed to $O(G_F)$ for magnetized target (Stodolsky; LSS) but very small

- Other: induced phonons, superconducting currents, etc., small

- Large μ_ν? (PL, Davoudiasl)

Big Bang Nucleosynthesis

- **Parameters**
  - $\eta = n_B/n_\gamma$ ($\eta_{10} \sim 274\ \Omega_b h^2$)
  - ΔN_ν (any new source of energy density, relative to one active ν flavor)
  - $\xi_e = \mu_{\nu_e}/T$, related to $(N_{\nu_e} - N_{\bar{\nu}_e})/n_\gamma$
- **SBBN:** $\Delta N_\nu = \xi_e = 0$

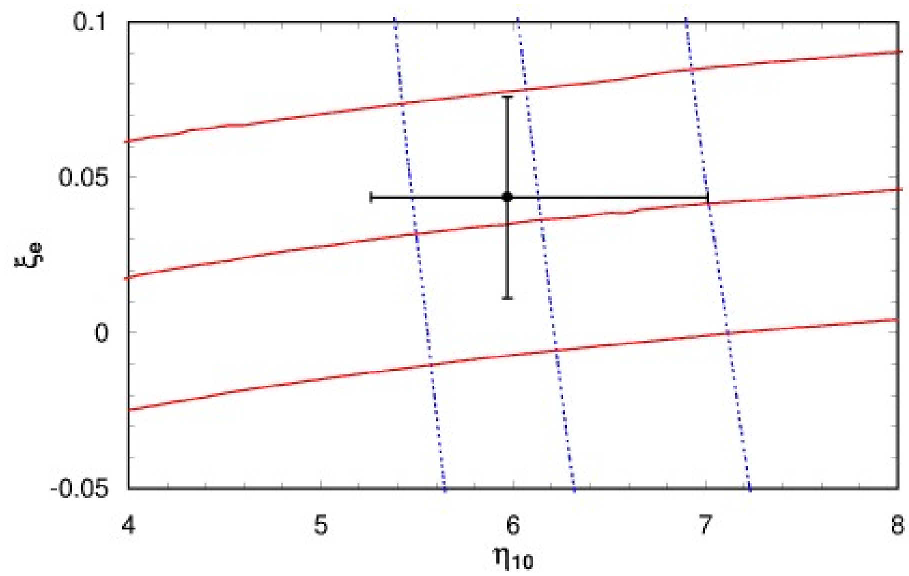
- $\nu_e n \leftrightarrow e^- p$ **and** $e^+ n \leftrightarrow \bar{\nu}_e p$ **keep** n_n/n_p **in equilibrium as long as it is rapid enough**

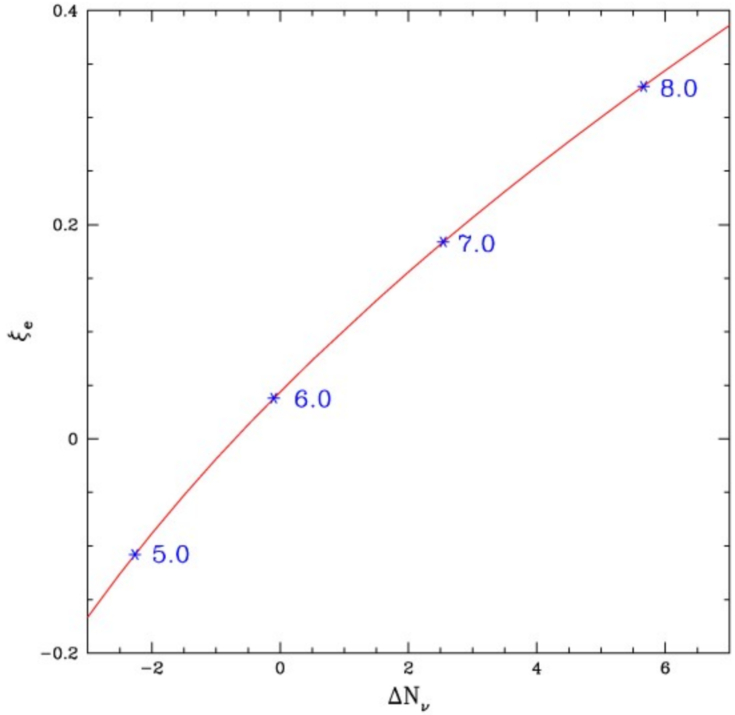
- $\nu_e n \leftrightarrow e^- p$ and $e^+ n \leftrightarrow \bar{\nu}_e p$ keep n_n/n_p in equilibrium as long as it is rapid enough
  - Freezeout at $T_\star \sim 1$ MeV, when $\Gamma_{\rm weak} \sim H$
  - $\Gamma_{\rm weak} = c G_F^2 T^5$
  - $H = \left[\frac{8\pi}{3} G_N \rho\right]^{1/2} \sim 1.66 g_\star^{1/2} T^2 / M_{Pl}$
  - $g_\star = g_B + \frac{7}{8} g_F$, with $g_F = 10 + 2\Delta N_\nu$
  - $T_\star \sim \left(\frac{n_\star^{1/2}}{G_F^2 M_{Pl}}\right)^{1/3}$
  - $\frac{n_n}{n_p} = e^{-(m_n - m_p + \mu_{\nu_e})/T_\star} \longrightarrow {}^4He$
  - ${}^4He$ mass fraction: $Y_p = \frac{4 n_{^4He}}{n_H}$ depends strongly on ΔN_ν ($\Delta Y_p \sim 0.013 \Delta N_\nu$) and ξ_e, weakly on η
  - $Y_2 = \frac{D}{H}$ depends on η (baryometer)
  - Independent determination of η from CMB

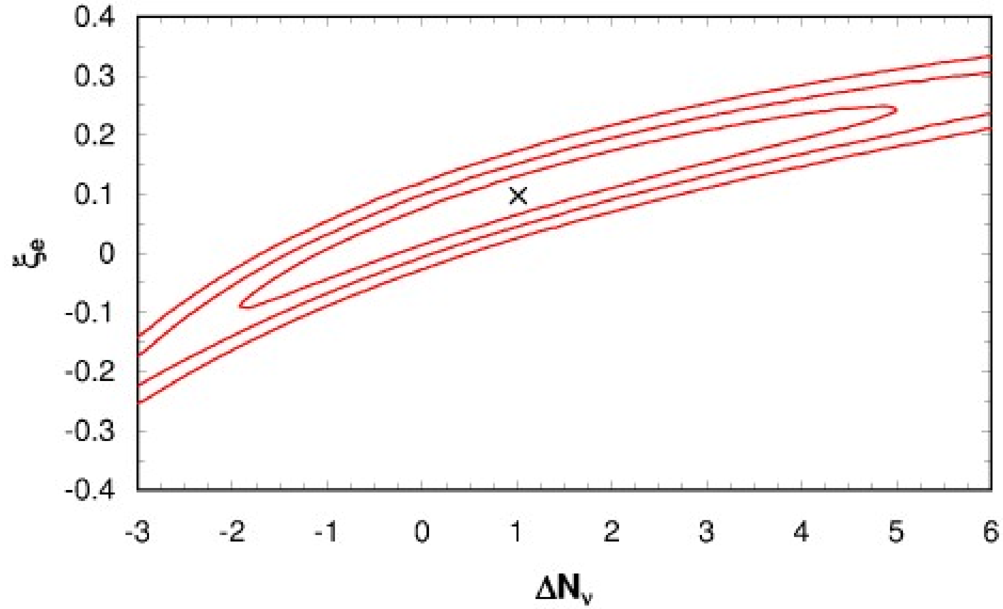
- **Data**
  - “High”: $Y_p^{\rm exp} = 0.244(2)$ (IT)
  - “Low”: $Y_p^{\rm exp} = 0.234(3)$ (OS)
  - Will use $Y_P = 0.238 \pm 0.005$
  - High D/H not confirmed (hydrogen interloper?) in absorption of background quasars $\longrightarrow$ use Low $y_D = 10^5(D/H) = 2.6 \pm 0.4$
  - $\Omega_b h^2(D/H) = 0.020(2)$
  - $\Omega_b h^2(\mathrm{CMB}) \sim 0.0224(9)$ (DASI, BOOMERanG, MAXIMA,WMAP).

- **Nonstandard BBN**
  - Typical range: $-1.5 < \Delta N_\nu - 16.6\xi_e < 0.3$
  - Most contributions to ΔN_ν are positive (decaying ν_τ could be negative, but small parameter range)
  - Compensations with $\xi_e > 0$ possible (not equilibrated $\xi_{\mu,\tau}$)

  - Best $\Delta N_\nu = 0$ fit for $\xi_e \neq 0$.
  - Data point for $y_D = 2.6 \pm 0.4$, $Y_P = 0.238 \pm 0.005$. (Barger, Kneller, PL, Marfatia, Steigman)







Central values of ξ_e as a function of ΔN_ν. The corresponding central values of $10^{10}\eta$ are also shown.

Allowed regions of ξ_e and ΔN_ν from helium and deuterium, including WMAP constraints (Barger, Kneller, PL, Marfatia, Steigman).

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  - Produced by mass effects for $m_\nu \gtrsim 10$ keV
  - New weak interactions: e.g. $f\bar{f} \rightarrow \nu_R \bar{\nu}_R$ by Z' or $Z - Z'$ mixing (Olive, Schramm, Steigman)
  - Results model dependent. Detailed calculations yield large ΔN_ν in E_6 models. (Suppressed in $Z' \nu_R \bar{\nu}_R$ decoupling limit.) (Barger, Lee, PL, PR D67)

- Ordinary-sterile mixing in 4 ν schemes
  - Produce ν_s by oscillations and active scattering (decoherence) $\rightarrow \Delta N_\nu \sim 1$
  - Solar SMA into sterile would have been allowed, but not larger Δm^2 or mixings
  - Self-suppression (BFV,SFA): $\Delta L \neq 0 \Rightarrow$ could self-generate lepton asymmetries to either (a) suppress sterile production or (b) generate compensating ξ_e

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  - Self-suppression now excluded for all 3+1 and 2+2 parameters (Di Bari, PR D65). (Also, solar + atm. fits (Maltoni et al, NP B643)).
  - Could save with large ($O(1)$) preexisting asymmetry or 5th (heavier) sterile ν_s leading to asymmetry

The GUT Seesaw

- Elegant mechanism for small Majorana masses
- Leptogenesis
- Expect small mixings in simplest versions (can evade by lopsided e/d, Majorana textures, etc.)
- Large Majorana often forbidden, e.g., by extra $U(1)$'s
- Direct Majorana masses and large scales forbidden in some string constructions
- GUTs, adjoint Higgs, large Higgs hard to accomodate in simplest heterotic constructions

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  – Small Majorana from loops, R_p violation, or TeV seesaw
  – Small Dirac from large extra dimension or by higher dimensional operators in intermediate scale models (e.g. $U(1)'$)

$$L_\nu \sim \left(\frac{S}{M_{Pl}}\right)^p L N_L^c H_2, \quad \langle S \rangle \ll M_{Pl}$$

$$\Rightarrow m_\nu \sim \left(\frac{\langle S \rangle}{M_{Pl}}\right)^p \langle H_2 \rangle$$

(flexible seesaw alternative; can also yield large ordinary-sterile mixing (PL))

A TeV scale Z'?

- Motivations
  - Strings, GUTs, DSB often involve extra $U(1)'$(GUTs require extra fine tuning for $M_{Z'} \ll M_{\mathrm{GUT}}$)
  - String models: radiative breaking of electroweak (SUGRA or gauge mediated) often yield ew/TeV scale Z' (unless breaking along flat direction $\longrightarrow$ intermediate scale)
  - Solution to μ problem

$$W \sim hSH_uH_d,$$

S = standard model singlet, charged under $U(1)'$. $\langle S \rangle$ breaks $U(1)'$, $\mu_{eff} = h\langle S \rangle$ (like NMSSM, but no domain walls)

- Experimental limits (precision and collider) model dependent, but typically $M_{Z'} > (500 - 800)\ GeV$ and $Z - Z'$ mixing $|\delta| <$ few$\times 10^{-3}$

- Models: $M_{Z'} \gtrsim 10 M_Z$ by either modest tuning (Demir et al), or by secluded sector (Erler, PL, Li)

- Implications
  - Exotics
  - FCNC (especially in string models)
  - Non-standard Higgs masses, couplings (doublet-singlet mixing)
  - Non-standard sparticle spectrum
  - Enhanced possibility of EW baryogenesis (Han, Kang, PL, Li)

Big Bang Nucleosynthesis Constraints on Z'

(Barger, Lee, PL, PR D67, 2003)

- Suppose $U(1)'$ forbids large Majorana mass for ν_R needed for traditional seesaw $\Rightarrow$ need TeV seesaw or small Dirac masses
- $\nu_L \bar{\nu}_L, e^+ e^- \rightarrow Z' \rightarrow \nu_R \bar{\nu}_R$ (or $W' \rightarrow e \nu_R$, etc) can produce ν_R efficiently prior to BBN (Olive, Schramm, Steigman, 1979)

- Rough estimate: $\sigma_{Z'}/\sigma_Z \sim (M_Z/M_{Z'})^4$
- ν_R decouples for reaction rate $\Gamma_{Z'}(T) = n\langle\sigma_{Z'}v\rangle \sim G_W^2(M_Z/M_{Z'})^4 T^5$ comparable to expansion rate $H \sim T^2/M_{Pl}$ at,

$$T_d(\nu_R) \;\sim \left(\frac{M_{Z'}}{M_Z}\right)^{4/3} T_d(\nu_L),$$

  where $T_d(\nu_L) \sim$ few MeV.
- ν_R subsequently diluted by annihilations of heavy particles ($c,\ \tau,\ s,\ \mu,\ \pi$) and by the confinement of quarks and gluons at quark-hadron transition at $T_c \sim 150 - 400$ MeV (these reheat $e^{\pm},\ \nu_L, \gamma$ but not ν_R

- **Full treatment requires detailed contributions of heavy particles to interactions, expansion rate, and entropy; and $Z - Z'$ mixing**
  - **For three types of right-handed neutrinos**

$$\Delta N_\nu = 3 \cdot \left(\frac{T_{\nu_R}}{T_{BBN}} \right)^4 = 3 \left(\frac{g(T_{BBN})}{g(T_d(\nu_R))} \right)^{4/3},$$

Follows from entropy conservation.

$T_d(\nu_R)$ is the ν_R decoupling temperature, $g(T) \sim g_B(T) + \frac{7}{8} g_F(T)$ (+ mass effects), $g_{B,F}(T)$ are the number of bosonic and fermionic relativistic degrees of freedom in equilibrium at temperature T.

– $g(T_{BBN}) = 43/4$ from the three active neutrinos, $e^{\pm}$, and γ, and $g(T)$ increases (in this approximation) as a series of step functions at higher temperature. Above quark-hadron temperature $T_c \sim 150 - 400\ MeV$ include quarks and gluons $(u,\ d,\ s, \cdots)$; below T_c may have pions.

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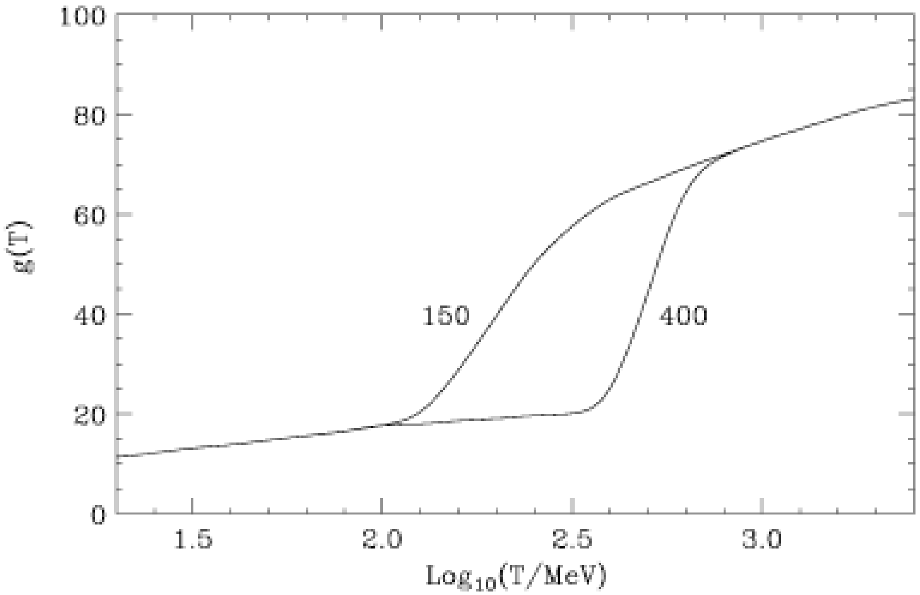


$g(T)$ for $T_c = 150$ and $400 \; MeV$, not including the three ν_R (Olive et al.)

– Find $T_d(\nu_R)$ by comparing $\overline{\nu_R}\nu_R$ annihilation rate

$$\Gamma(T) = \sum_i \Gamma_i(T) = \sum_i \frac{n_{\nu_R}}{g_{\nu_R}} \left\langle \sigma v(\overline{\nu_R}\nu_R \to \overline{f}_i f_i,\ \pi^+\pi^-) \right\rangle,$$

with expansion rate

$$H(T) = \sqrt{\frac{8\pi G_N \rho(T)}{3}} = \sqrt{\frac{4\pi^3 G_N g'(T)}{45}} T^2,$$

with $g'(T) = g(T) + \frac{21}{4}$, for the 3 ν_R.

– For $\sigma_i(s) \equiv \sigma(\overline{\nu_R}\nu_R \to \overline{f_i} f_i)$

$$\begin{aligned}\sigma_i(s) &= N_C^i \frac{s\beta_i}{16\pi}\left\{\left(1+\frac{\beta_i^2}{3}\right)\left((G_{RL}^i)^2+(G_{RR}^i)^2\right)\right. \\ &\quad \left. + 2\left(1-\beta_i^2\right) G_{RL}^i G_{RR}^i\right\}\end{aligned}$$

where (for $s \ll M_{Z_1}^2, M_{Z_2}^2$)

$$\begin{aligned}G_{RX}^i &= g_Z'^2 Q(\nu_R) Q(f_{iX})\left(\frac{\sin^2\delta}{M_{Z_1}^2}+\frac{\cos^2\delta}{M_{Z_2}^2}\right) \\ &- g_Z' g_Z Q(\nu_R) Q_Z(f_{iX})\left(\frac{\sin\delta\cos\delta}{M_{Z_1}^2}-\frac{\sin\delta\cos\delta}{M_{Z_2}^2}\right),\end{aligned}$$

$Q(Q_Z) = Z'(Z)$ charge, $X = L$ or R, $\beta_i \equiv \sqrt{1-4m_{f_i}^2/s}$, N_C^i is the color factor of f_i, and $\delta = Z - Z'$ mixing angle.

The E_6 $U(1)'$ Model

- Standard anomaly-free $U(1)'$ model, but not full GUT (proton decay)

- Two $U(1)'$ factors

$$E_6 \longrightarrow SO(10) \times U(1)_\psi \longrightarrow SU(5) \times U(1)_\chi \times U(1)_\psi$$

Assume one light, with charge

$$Q = Q_\chi \cos\theta_{E6} + Q_\psi \sin\theta_{E6}$$

Special case, $U(1)_\eta$: $\theta_{E6} = 2\pi - \tan^{-1}\sqrt{\frac{5}{3}} = 1.71\pi.$

The (family-universal) charges of the $U(1)_\chi$ and the $U(1)_\psi$.

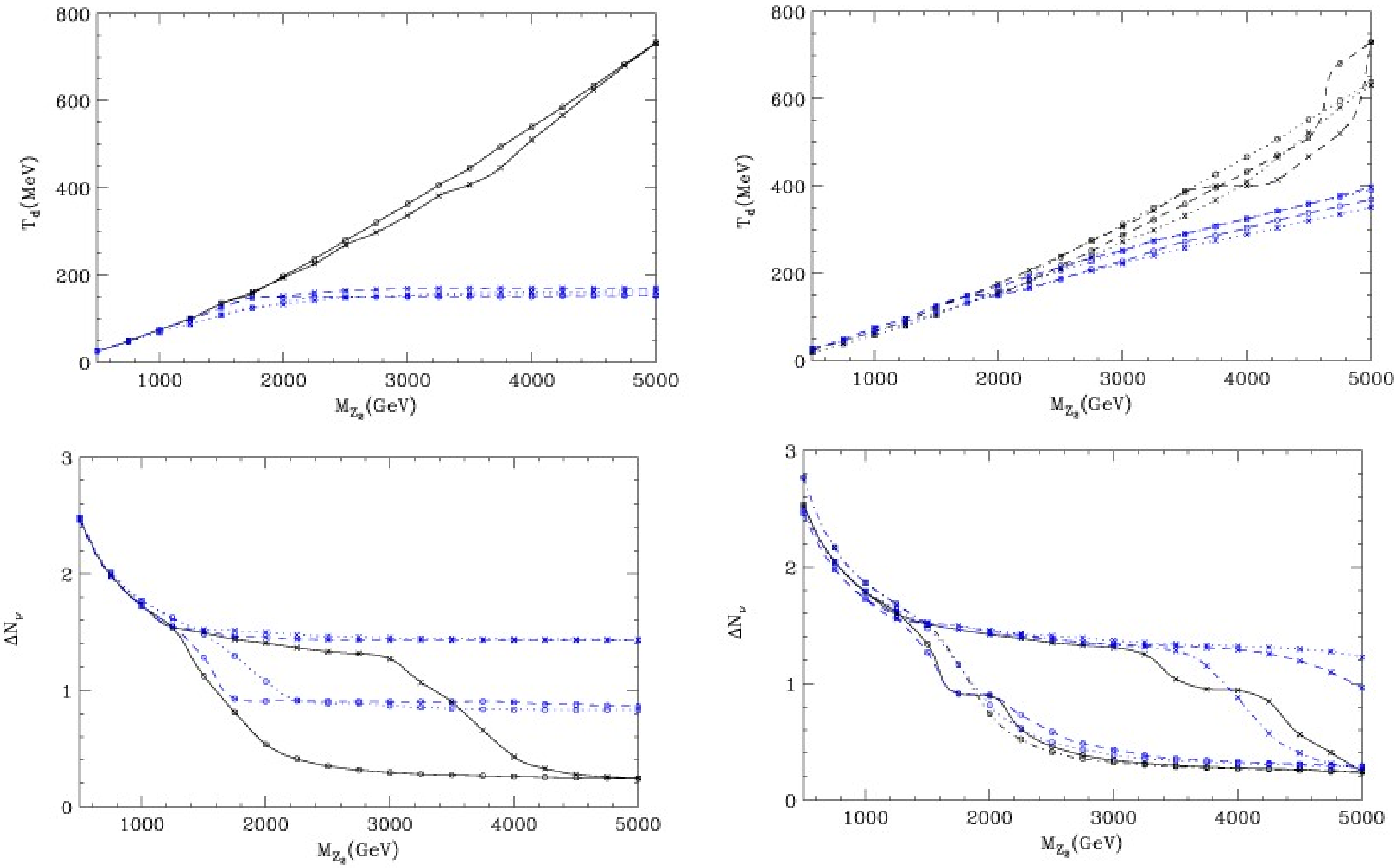
Fields	Q_χ	Q_ψ
u_L	$-1/2\sqrt{10}$	$1/2\sqrt{6}$
u_R	$1/2\sqrt{10}$	$-1/2\sqrt{6}$
d_L	$-1/2\sqrt{10}$	$1/2\sqrt{6}$
d_R	$-3/2\sqrt{10}$	$-1/2\sqrt{6}$
e_L	$3/2\sqrt{10}$	$1/2\sqrt{6}$
e_R	$1/2\sqrt{10}$	$-1/2\sqrt{6}$
ν_L	$3/2\sqrt{10}$	$1/2\sqrt{6}$
ν_R	$5/2\sqrt{10}$	$-1/2\sqrt{6}$

- $Z - Z'$ **mixing** δ

$$
\begin{array}{llll}
\textbf{(A0)} & \delta & = & \mathbf{0} \;\; \textbf{(no mixing)} \\
\textbf{(A1)} & |\delta| & < & \mathbf{0.0051}/M_{Z_2}^2 \;\; \textbf{(mass} - \textbf{mixing relation for 27} - \textbf{plet)} \\
\textbf{(A2)} & |\delta| & < & \mathbf{0.0029}/M_{Z_2} \;\; \textbf{(}\rho_0 \textbf{ constraint)} \\
\textbf{(A3)} & |\delta| & = & \mathbf{0.002} \;\; \textbf{(maximal mixing allowed for } M_{Z_2} \sim 1 \; TeV\textbf{).}
\end{array}
$$

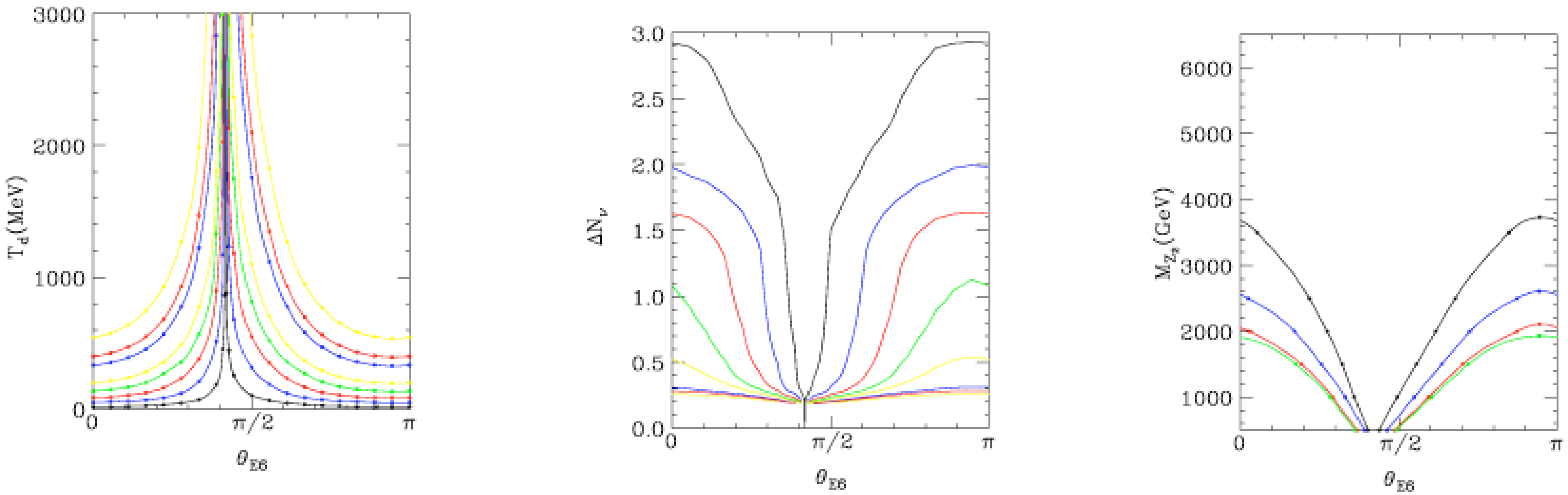
(A1 more stringent than A2 and A3 in the large mass range)

Results for the η Model



T_d (top) and ΔN_ν (bottom) for the η model, for $T_c = 150$ MeV (circles) and 400 MeV (crosses). Left: A0 and A3. Right: A1 and A2.

Results for the General E_6 Model



T_d (left) and ΔN_ν (middle) for $M_{Z_2} =$ 500, 1000, 1500, 2000, 2500, 3500, 4000, and 5000 GeV, for $T_c = 150$ MeV and no mixing. Larger M_{Z_2} corresponds to higher T_d and smaller ΔN_ν. Right: M_{Z_2} corresponding to $\Delta N_\nu = 0.3,\ 0.5,\ 1.0$ and 1.2, with larger ΔN_ν corresponding to smaller M_{Z_2}. χ, ψ, and $-\eta$ correspond to $\theta_{E6} = 0,\ \pi/2,\ 0.71\pi$. The results including mixing are similar.

- Very sensitive to θ_{E6}, δ, and T_c
- η model
  - $\Delta N_\nu < 0.3 \Rightarrow M_{Z'} > (2.5 - 3.2)\ TeV$ for $T_c = 150\ MeV$
  - $\Delta N_\nu < 0.3 \Rightarrow M_{Z'} > (4.0 - 4.9)\ TeV$ for $T_c = 400\ MeV$
- General E_6 case (all mixing assumptions)
  - $\Delta N_\nu < 0.3$ for all θ_{E6} for $M_{Z'} > 2.4\ TeV$ $(T_c = 150\ MeV)$ (more stringent for $T_c = 400\ MeV$)
  - Limits disappear near ν_R decoupling angle $\theta_{E6} = 0.42\pi$ ($\chi = 0,\ \psi = \pi/2,\ -\eta = 0.71\pi$)
- Constraints often much more stringent than current direct/indirect; comparable to LHC range
- For $\Delta N_\nu < 0.3$, somewhat more stringent than supernova limits, but different uncertainties.

Implications

- $U(1)'$ may forbid traditional GUT-scale seesaw
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Implications

- $U(1)'$ may forbid traditional GUT-scale seesaw
- Z' masses severely constrained for Dirac ν by BBN
- Ways out
  - TeV seesaw or other non-Dirac mechanism
  - Large ξ_e asymmetry (equilibration limits don't apply because of ΔN_ν)
  - ν_R decoupling from Z' (can occur naturally in $U(1)' \times U(1)'$ model)

Natural ν_R Decoupling in $U(1)'\times U(1)'$

- Break $U(1)'\times U(1)'$ by standard model singlets $\tilde{\nu}_R + \tilde{\nu}^*_R$ and $\tilde{s}_L + \tilde{s}^*_L$ from 27, 27^*-plets. D terms:

$$
\begin{aligned}
V_\chi + V_\psi &= \frac{g'^2}{2}\left[\frac{5}{2\sqrt{10}}(|\tilde{\nu}_R|^2 - |\tilde{\nu}^*_R|^2)\right]^2 \\
&+ \frac{g'^2}{2}\left[\frac{1}{\sqrt{24}}(-|\tilde{\nu}_R|^2 + |\tilde{\nu}^*_R|^2 - 4|\tilde{s}_L|^2 + 4|\tilde{s}^*_L|^2)\right]^2,
\end{aligned}
$$

Natural ν_R Decoupling in $U(1)'\times U(1)'$

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$$\begin{aligned} V_\chi + V_\psi &= \frac{g'^2}{2}\left[\frac{5}{2\sqrt{10}}(|\tilde{\nu}_R|^2 - |\tilde{\nu}^*_R|^2)\right]^2 \\ &+ \frac{g'^2}{2}\left[\frac{1}{\sqrt{24}}(-|\tilde{\nu}_R|^2 + |\tilde{\nu}^*_R|^2 - 4|\tilde{s}_L|^2 + 4|\tilde{s}^*_L|^2)\right]^2, \end{aligned}$$

- D-flat for $|\tilde{\nu}_R|^2 = |\tilde{\nu}^*_R|^2 \equiv |\tilde{\nu}|^2$ and $|\tilde{s}_L|^2 = |\tilde{s}^*_L|^2 \equiv |\tilde{s}|^2$. May also be F-flat, broken by soft masses,

$$V(\tilde{\nu}, \tilde{s}) = m^2_{\tilde{\nu}}|\tilde{\nu}^2| + m^2_{\tilde{s}}|\tilde{s}^2|$$

- Z' **mass terms**

$$\begin{aligned}\mathcal{L} &= g'^2\left(-\frac{5}{2\sqrt{10}}Z_\chi + \frac{1}{\sqrt{24}}Z_\psi\right)^2\left(|\tilde{\nu}_R|^2 + |\tilde{\nu}_R^*|^2\right)\\ &\quad + g'^2\left(\frac{4}{\sqrt{24}}Z_\psi\right)^2\left(|\tilde{s}_L|^2 + |\tilde{s}_L^*|^2\right)\end{aligned}$$

- Z' mass terms

$$\mathcal{L} = g'^2 \left(-\frac{5}{2\sqrt{10}} Z_\chi + \frac{1}{\sqrt{24}} Z_\psi\right)^2 \left(|\tilde{\nu}_R|^2 + |\tilde{\nu}_R^*|^2\right)$$
$$+ g'^2 \left(\frac{4}{\sqrt{24}} Z_\psi\right)^2 \left(|\tilde{s}_L|^2 + |\tilde{s}_L^*|^2\right)$$

For $m_{\tilde{s}}^2 > 0$ and $m_{\tilde{\nu}}^2 < 0$ the breaking will occur along $|\tilde{\nu}_R| = |\tilde{\nu}_R^*|$ very large, with the potential ultimately stabilized by loop corrections or higher dimensional operators. $\tilde{s}_L$ and $\tilde{s}_L^*$ will acquire (usually different) TeV-scale expectation values.

- $Z_1 \equiv \frac{1}{\sqrt{24}} Z_\chi + \frac{5}{2\sqrt{10}} Z_\psi$ at TeV scale (Z_1 decouples from ν_R, avoiding BBN, supernova constraints)
- $Z_2 \equiv -\frac{5}{2\sqrt{10}} Z_\chi + \frac{1}{\sqrt{24}} Z_\psi$ superheavy (can use Z_2 scale for small Dirac ν_R mass by HDO)

Conclusions

- Relic neutrinos important for BBN, CMB, structure, ν mass spectrum
- Direct detection extremely difficult. Z burst?
- Z' very well motivated, but may forbid canonical large-scale seesaw
- Light Dirac (e.g., by HDO) produced efficiently by Z'
  - Strong BBN constraints
  - Relax by ξ_e asymmetry or ν_R decoupling